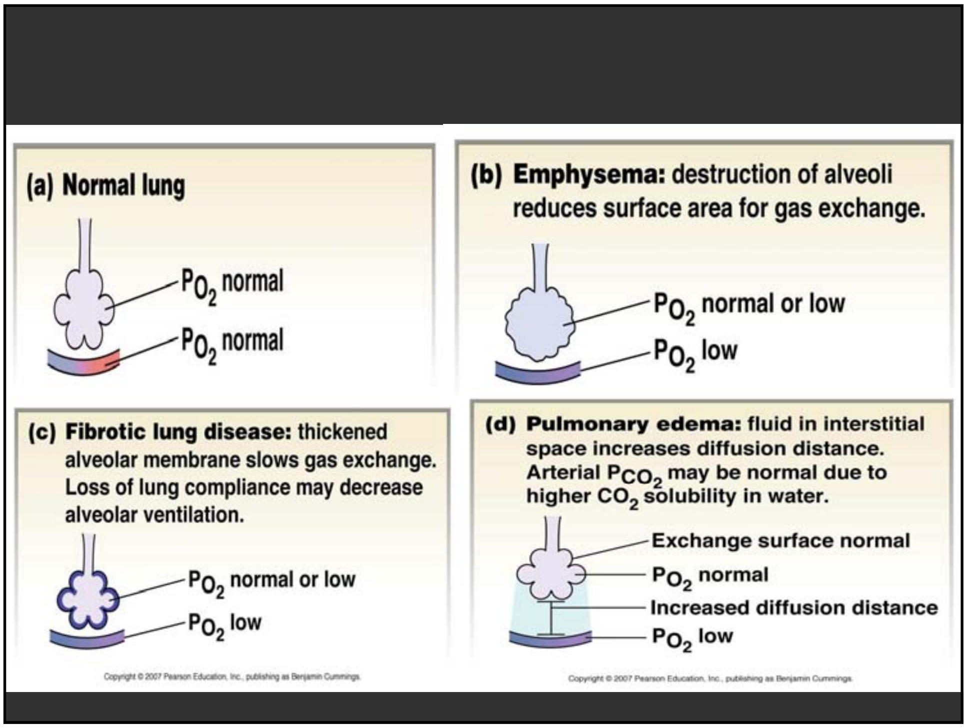
Lung Volumes and Capacities

To review first

4 rules for diffusion of gas
- Surface area
- Thickness
- Concentration
- Distance


(a) Normal lung
P_{O_2} normal
P_{O_2} normal
(b) Emphysema: destruction of alveoli reduces surface area for gas exchange.
P_{O_2} normal or low
P_{O_2} low
(c) Fibrotic lung disease: thickened alveolar membrane slows gas exchange. Loss of lung compliance may decrease alveolar ventilation.
P_{O_2} normal or low
P_{O_2} low
(d) Pulmonary edema: fluid in interstitial space increases diffusion distance. Arterial P_{CO_2} may be normal due to higher CO_2 solubility in water.
Exchange surface normal
P_{O_2} normal
Increased diffusion distance
P_{O_2} low
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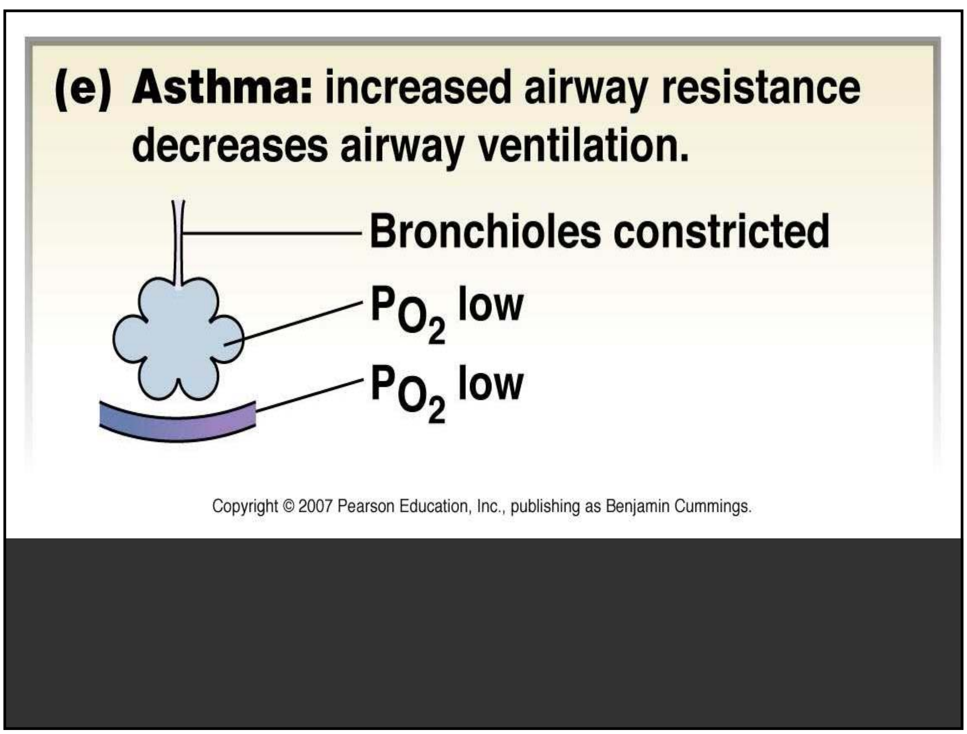
(e) Asthma: increased airway resistance decreases airway ventilation.
Bronchioles constricted
P_{O_2} low
P_{O_2} low
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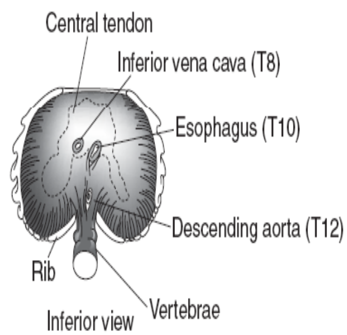
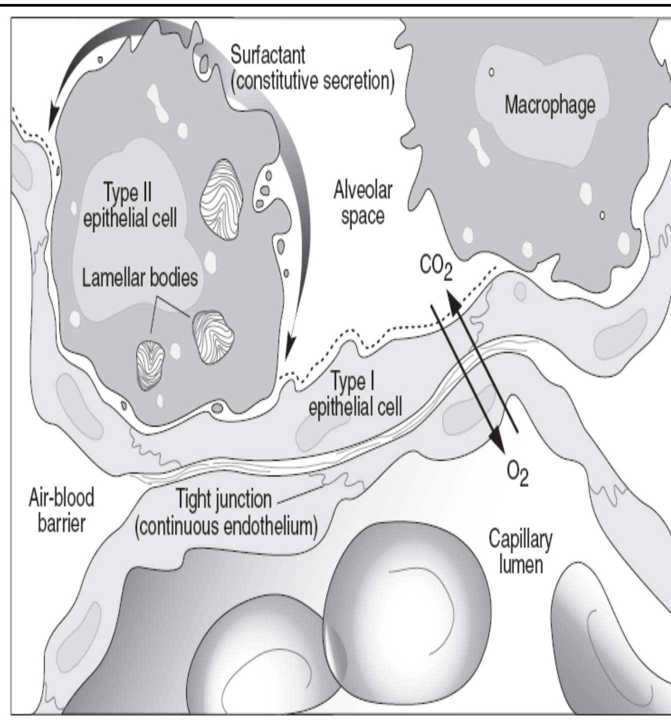
Diaphragm structures	Structures perforating diaphragm: At T8: IVC. At T10: esophagus, vagus (2 trunks). At T12: aorta (red), thoracic duct (white), azygous vein (blue). Diaphragm is innervated by C3, 4, and 5 (phrenic nerve). Pain from the diaphragm can be referred to the shoulder.	Number of letters = T level: T8: vena cava T10: (o)esophagus T12: aortic hiatus "C3, 4, 5 keeps the diaphragm alive."



Gas exchange barrier



Pneumocytes	Pseudocolumnar ciliated cells extend to the respiratory bronchioles; goblet cells extend only to the terminal bronchioles. Type I cells (97% of alveolar surfaces) line the alveoli. Squamous; thin for optimal gas diffusion. Type II cells (3%) secrete pulmonary surfactant (dipalmitoyl phosphatidylcholine), which ↓ the alveolar surface tension. Cuboidal and clustered. Also serve as precursors to type I cells and other type II cells. Type II cells proliferate during lung damage. Clara cells—nonciliated; columnar with secretory granules. Secrete component of surfactant; degrade toxins; act as reserve cells.	Mucus secretions are swept out of the lungs toward the mouth by ciliated cells. A lecithin-to-sphingomyelin ratio of > 2.0 in amniotic fluid is indicative of fetal lung maturity.

- **The following terms describe the various lung (respiratory) volumes:**
- **The tidal volume (TV),** about 500 ml, is the ***amount of air inspired during normal, relaxed breathing***.
- **The inspiratory reserve volume (IRV),** about 3,100 ml, is the ***additional air that can be forcibly inhaled after the inspiration of a normal tidal volume***.
- **The expiratory reserve volume (ERV),** about 1,200 ml, is ***the additional air that can be forcibly exhaled after the expiration of a normal tidal volume.***
- **Residual volume (RV),** about 1,200 ml, ***is the volume of air still remaining in the lungs after the expiratory reserve volume is exhaled.***

Summing specific lung volumes produces the following lung capacities:

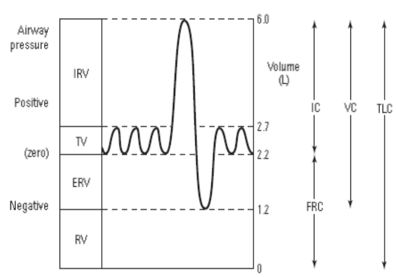
- **The total lung capacity (TLC),** about **6,000 ml**, **is the maximum amount of air that can fill the lungs**
  - (*TLC = TV + IRV + ERV + RV*).
- **The vital capacity (VC),** about **4,800 ml**, is **the total amount or air that can be expired after fully inhaling**
  - ***(VC = TV + IRV + ERV = approximately 80% TLC).***
- **The inspiratory capacity (IC),** about **3,600 ml**, is **the maximum amount of air that can be inspired**
  - ***(IC = TV + IRV).***
- **The functional residual capacity (FRC),** about **2,400 ml**, **is the amount of air remaining in the lungs after a normal expiration**
  - (FRC = RV + ERV).
- Some of the air in the lungs does not participate in gas exchange. Such air is located in the anatomical dead space within bronchi and bronchioles—that is, outside the alveoli.

Dead Space

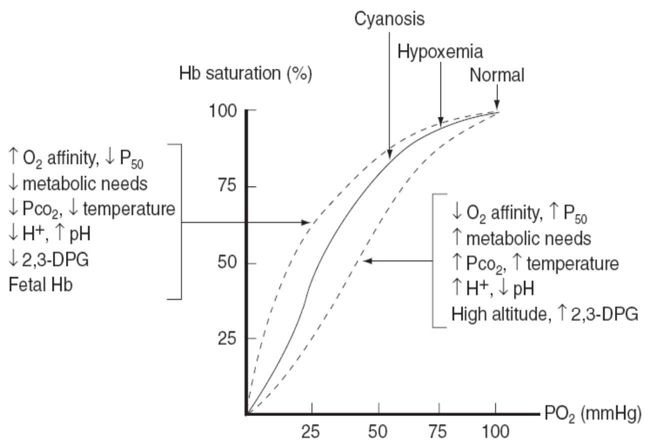
- Anatomical dead space – volume of the conducting respiratory passages (150 ml)
- Alveolar dead space – alveoli that cease to act in gas exchange due to collapse or obstruction
- Total dead space – sum of alveolar and anatomical dead spaces

Muscles of respiration	Quiet breathing: Inspiration––diaphragm. Expiration––passive. Exercise: Inspiration––external intercostals, scalene muscles, sternomastoids. Expiration––rectus abdominis, internal and external obliques, transversus abdominis, internal intercostals.	
Important lung products	1. Surfactant—produced by type II pneumocytes, ↓ alveolar surface tension, ↑ compliance, ↓ work of inspiration 2. Prostaglandins 3. Histamine ↑ bronchoconstriction 4. Angiotensin-converting enzyme (ACE)—angiotensin I → angiotensin II; inactivates bradykinin (ACE inhibitors ↑ bradykinin and cause cough, angioedema) 5. Kallikrein—activates bradykinin	**Surfactant**––dipalmitoyl phosphatidylcholine (lecithin) deficient in neonatal RDS. Collapsing pressure = $\frac{2\ (\text{tension})}{\text{radius}}$

Lung volumes	1. Residual volume (RV)—air in lung after maximal expiration 2. Expiratory reserve volume (ERV)—air that can still be breathed out after normal expiration 3. Tidal volume (TV)—air that moves into lung with each quiet inspiration, typically 500 mL 4. Inspiratory reserve volume (IRV)––air in excess of tidal volume that moves into lung on maximum inspiration 5. Vital capacity (VC)––TV + IRV + ERV 6. Functional residual capacity (FRC)—RV + ERV (volume in lungs after normal expiration) 7. Inspiratory capacity (IC)—IRV + TV 8. Total lung capacity––TLC = IRV + TV + ERV + RV	Vital capacity is everything but the residual volume. A capacity is a sum of ≥ 2 volumes.



Oxygen-hemoglobin dissociation curve



Sigmoidal shape due to positive cooperativity, i.e., hemoglobin can bind 4 oxygen molecules and has higher affinity for each subsequent oxygen molecule bound.

When curve shifts to the right, ↓ affinity of hemoglobin for O_2 (facilitates unloading of O_2 to tissue).

An ↑ in all factors (except pH) causes a shift of the curve to the right.

A ↓ in all factors (except pH) causes a shift of the curve to the left.

Fetal Hb has a higher affinity for oxygen than adult Hb, so its dissociation curve is shifted left.

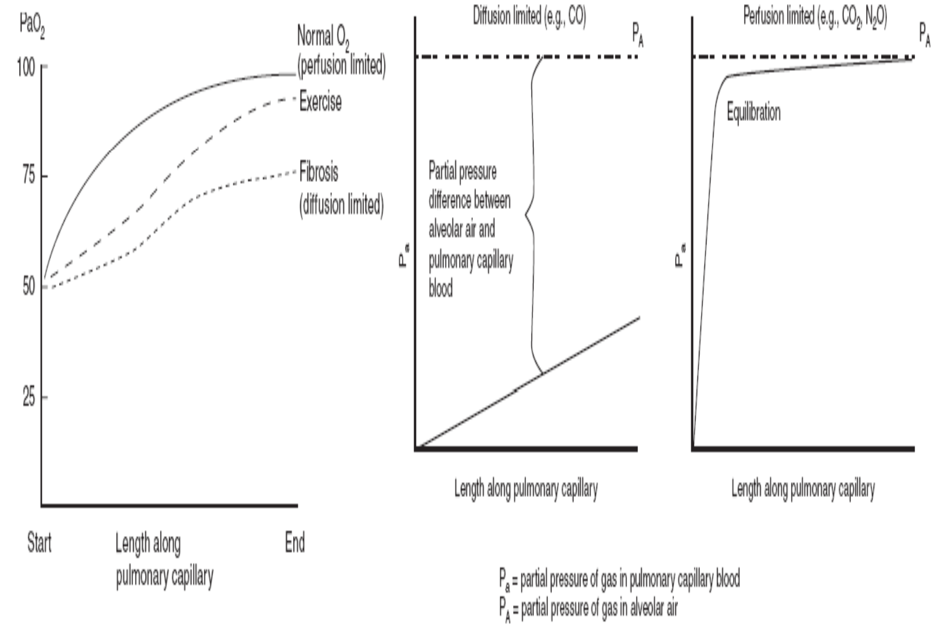
Right shift—**CADET** face **right:**
- **C**O_2
- **A**cid/Altitude
- **D**PG (2,3-DPG)
- **E**xercise
- **T**emperature

Pulmonary circulation

Normally a low-resistance, high-compliance system. Po_2 and Pco_2 exert opposite effects on pulmonary and systemic circulation. A ↓ in PaO_2 causes a hypoxic vasoconstriction that shifts blood away from poorly ventilated regions of lung to well-ventilated regions of lung.

1. Perfusion limited—O_2 (normal health), CO_2, N_2O. Gas equilibrates early along the length of the capillary. Diffusion can be ↑ only if blood flow ↑.
2. Diffusion limited—O_2 (emphysema, fibrosis), CO. Gas does not equilibrate by the time blood reaches the end of the capillary.

A consequence of pulmonary hypertension is cor pulmonale and subsequent right ventricular failure (jugular venous distention, edema, hepatomegaly).



Pulmonary vascular resistance (PVR)	$PVR = \dfrac{P_{pulm\ artery} - P_{L\ atrium}}{\text{Cardiac output}}$ Remember: $\Delta P = Q \times R$, so $R = \Delta P / Q$. $R = 8\eta l / \pi r^4$	$P_{pulm\ artery}$ = pressure in pulmonary artery. $P_{L\ atrium}$ = pulmonary wedge pressure. η = the viscosity of inspired air; l = airway length; r = airway radius.
Oxygen content of blood	O_2 content = (O_2 binding capacity × % saturation) + dissolved O_2. Normally 1 g Hb can bind 1.34 mL O_2; normal Hb amount in blood is 15 g/dL. Cyanosis results when Hb is < 5 g/dL. O_2 binding capacity ≈ 20.1 mL O_2 / dL. O_2 content of arterial blood ↓ as Hb falls, but O_2 saturation and arterial Po_2 do not. Arterial Po_2 ↓ with chronic lung disease because physiologic shunt ↓ O_2 extraction ratio. Oxygen delivery to tissues = cardiac output × oxygen content of blood.	

Alveolar gas equation

$$PA_{O_2} = PI_{O_2} - \frac{PA_{CO_2}}{R}$$

Can normally be approximated:

$PA_{O_2} = 150 - Pa_{CO_2} / 0.8$

PA_{O_2} = alveolar P_{O_2} (mmHg).
PI_{O_2} = P_{O_2} in inspired air (mmHg).
PA_{CO_2} = alveolar P_{CO_2} (mmHg).
R = respiratory quotient.
A-a gradient = $PA_{O_2} - Pa_{O_2}$ = 10–15 mmHg.
↑ A-a gradient may occur in hypoxemia; causes include shunting, V/Q mismatch, fibrosis (diffusion block).

V/Q mismatch

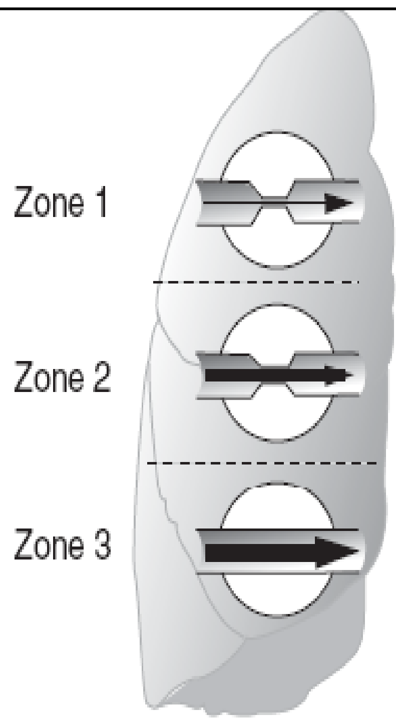
Ideally, ventilation is matched to perfusion (i.e., V/Q = 1) in order for adequate gas exchange to occur.

Lung zones:

1. Apex of the lung—V/Q = 3 (wasted ventilation)
2. Base of the lung—V/Q = 0.6 (wasted perfusion)

Both ventilation and perfusion are greater at the base of the lung than at the apex of the lung.

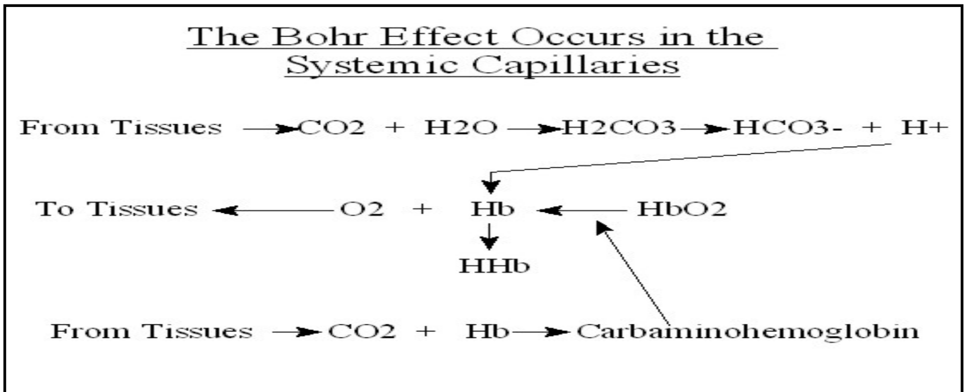
- With exercise (↑ cardiac output), there is vasodilation of apical capillaries, resulting in a V/Q ratio that approaches 1.
- Certain organisms that thrive in high O_2 (e.g., TB) flourish in the apex.
- $V/Q \rightarrow 0$ = airway obstruction (shunt). In shunt, 100% O_2 does not improve Po_2.
- $V/Q \rightarrow \infty$ = blood flow obstruction (physiologic dead space). Assuming < 100% dead space, 100% O_2 improves Po_2.



Apex: $P_A > P_a > P_v \rightarrow V/Q = 3$ (wasted ventilation)

$P_a > P_A > P_v$

Base: $P_a > P_v > P_A \rightarrow V/Q = 0.6$ (wasted perfusion); NOTE: both ventilation and perfusion are greater at the base of the lung than at the apex



The **Bohr Effect** describes the result of increasing CO_2 in causing more oxygen unloading from hemoglobin.

It results from two circumstances:

1) the effect of lowering pH as described above,
2) 2) the effect of carbaminohemoglobin in stimulating oxygen unloading

Main Gases of the Atmosphere

Gas	**Symbol**	**Approximate %**
Nitrogen	N2	78.6
Oxygen	O2	20.9
Carbon Dioxide	CO2	0.04
Water Vapor	H2O	0.46

Gas Exchange

- Partial Pressure
  - Each gas in atmosphere contributes to the entire atmospheric pressure, denoted as P
- Gases in liquid
  - Gas enters liquid and dissolves in proportion to its partial pressure
- O2 and CO2 Exchange by DIFFUSION
  - PO2 is 105 mmHg in alveoli and 40 in alveolar capillaries
  - PCO2 is 45 in alveolar capillaries and 40 in alveoli

Partial Pressures

- Oxygen is 21% of atmosphere
- 760 mmHg x .21 = 160 mmHg PO2
- This mixes with “old” air already in alveolus to arrive at PO2 of 105 mmHg

Partial Pressures

- Carbon dioxide is .04% of atmosphere
- 760 mmHg x .0004 = .3 mm Hg PCO_2
- This mixes with high CO_2 levels from residual volume in the alveoli to arrive at PCO_2 of 40 mmHg

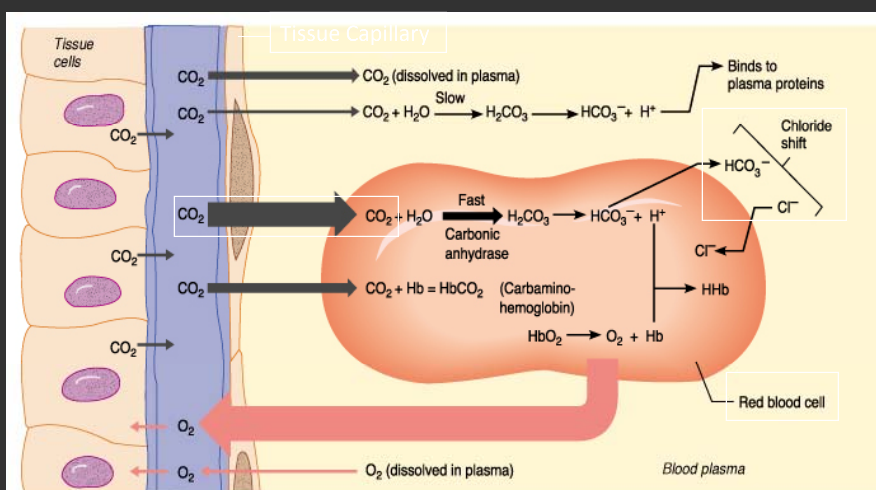
Carbon Dioxide Transport

Method	Percentage
Dissolved in Plasma	7 - 10 %
Chemically Bound to Hemoglobin in RBC's	20 - 30 %
As Bicarbonate Ion in Plasma	60 -70 %

Oxygen Transport

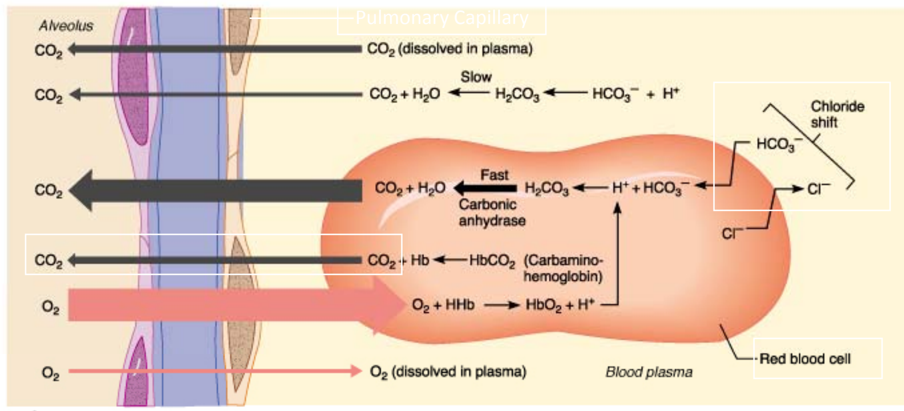
Method	Percentage
Dissolved in Plasma	1.5 %
Combined with Hemoglobin	98.5 %

Chloride Shift in Tissue Capillaries

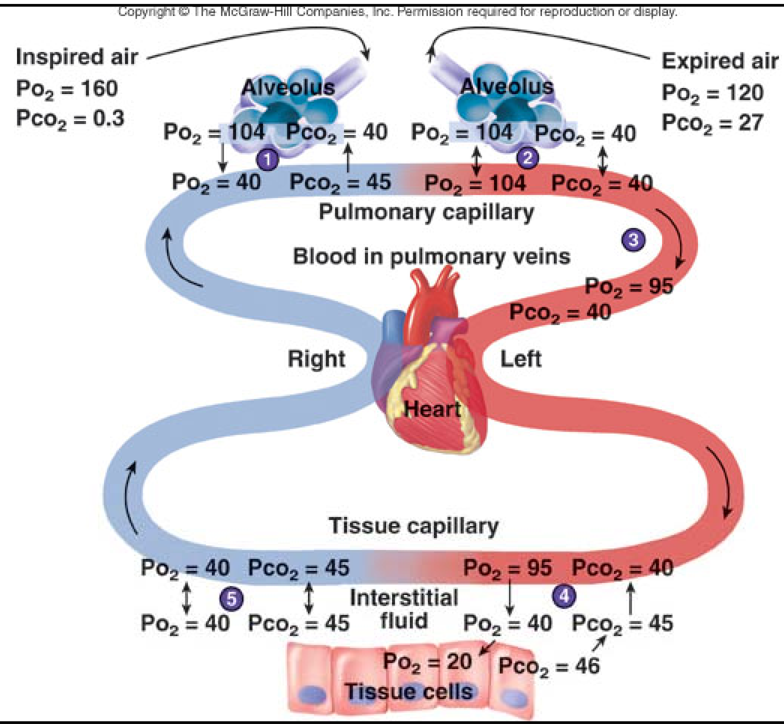


(a) Oxygen release and carbon dioxide pickup at the tissues

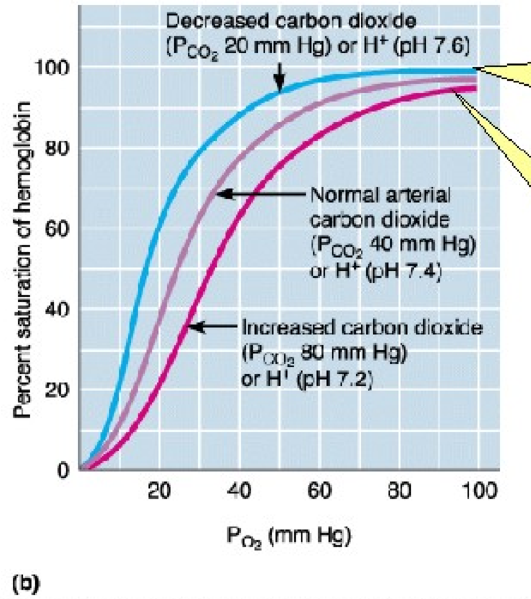
Chloride Shift in Pulmonary Capillaries



(b) Oxygen pickup and carbon dioxide release in the lungs

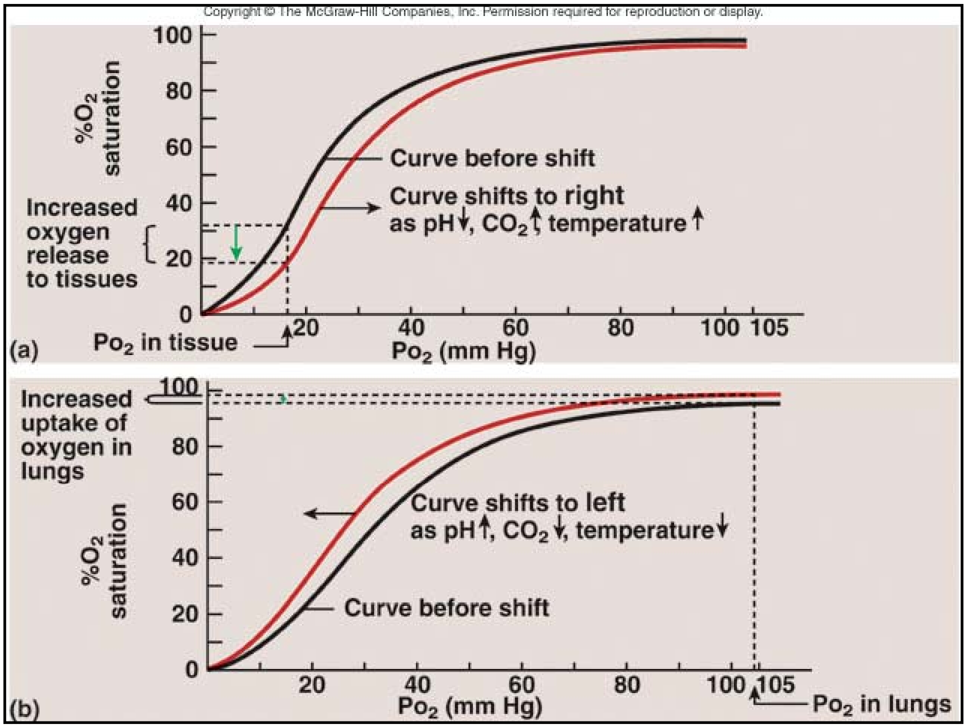


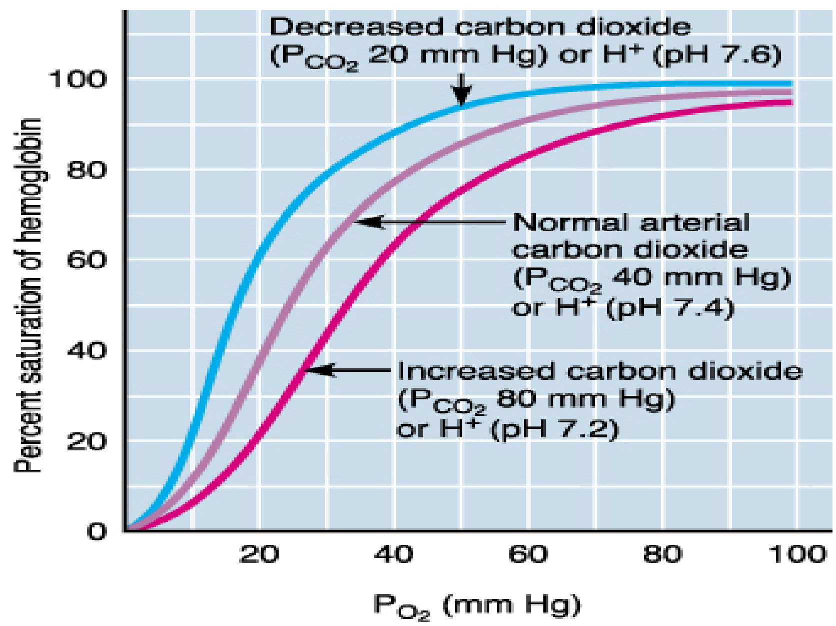
Effect of pH on Respiration



↑ pH resulting from ↓CO2 or H+ increases the association of oxygen with hemoglobin.

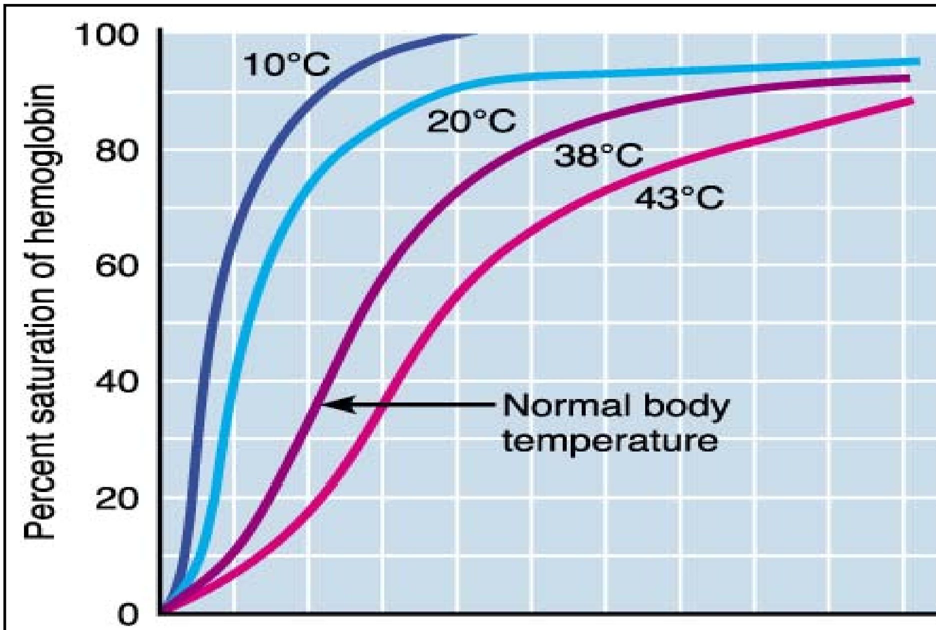
↓ pH resulting from ↑CO2 or H+ decreases the association of oxygen with hemoglobin.





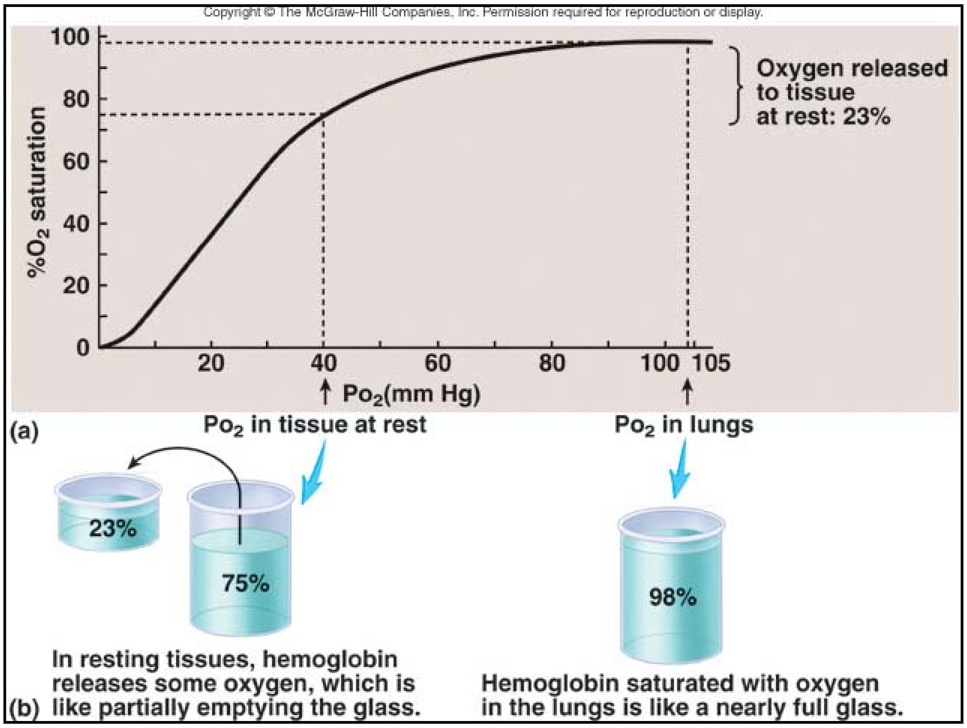
Decreased carbon dioxide
(P_{CO_2} 20 mm Hg) or H^+ (pH 7.6)
Normal arterial
carbon dioxide
(P_{CO_2} 40 mm Hg)
or H^+ (pH 7.4)
Increased carbon dioxide
(P_{CO_2} 80 mm Hg)
or H^+ (pH 7.2)
Percent saturation of hemoglobin
100
80
60
40
20
0
20
40
60
80
100
P_{O_2} (mm Hg)

(b)



10°C
20°C
38°C
43°C
Normal body
temperature
Percent saturation of hemoglobin
100
80
60
40
20
0

(a)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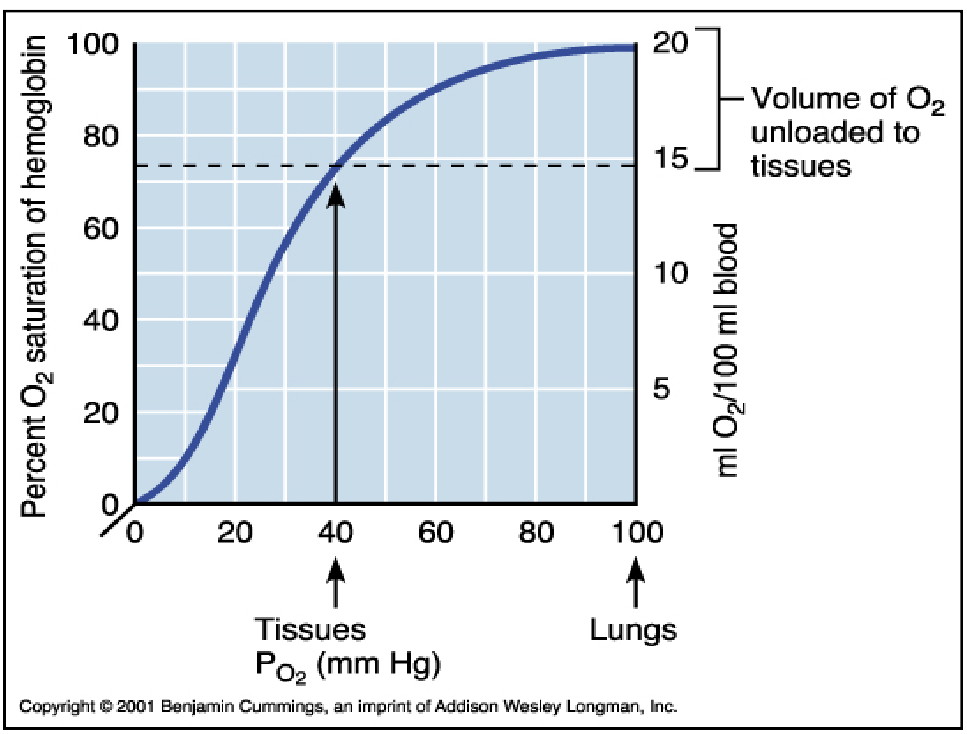
%O2 saturation
100
80
60
40
20
0
20
40
60
80
100
105
Po2(mm Hg)
Oxygen released to tissue at rest: 23%
(a)
Po2 in tissue at rest
Po2 in lungs
23%
75%
98%
In resting tissues, hemoglobin releases some oxygen, which is like partially emptying the glass.
Hemoglobin saturated with oxygen in the lungs is like a nearly full glass.
(b)


Percent O2 saturation of hemoglobin
100
80
60
40
20
0
0
20
40
60
80
100
20
15
10
5
ml O2/100 ml blood
Volume of O2 unloaded to tissues
Tissues
Lungs
PO2 (mm Hg)
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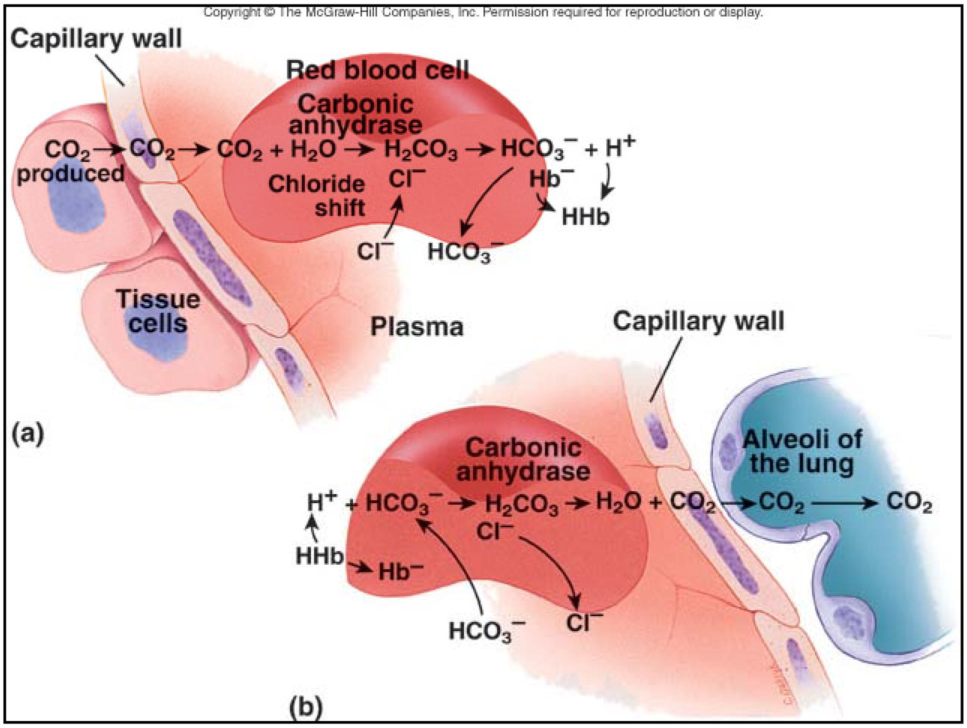

Factors Influencing Respiration